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Garment Selection for Cleanrooms and Controlled Environments for Spacecraft

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J. L. Buzzatto, Lt Col, USAF
Director of Support Operations Division
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Strict contamination control practices are exercised throughout the lifetime of a spacecraft in order to satisfy the performance requirements of the system. Spacecraft materials are carefully selected to have low outgassing values and particulate deposition. Parts are cleaned, and the vehicle is assembled in cleanrooms and work stations having controlled environments. This report covers specifications governing the selection of special items of clothing designed to protect spacecraft from contaminants released by personnel and by garments. Special clothing includes coveralls, footwear, and head/face covers. Garments appropriate for both hazardous (meltproof as well as flame resistant), and nonhazardous operations are described.

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PREFACE

I wish to thank Mrs. Sally Hill of Lockheed Space Operations Company (LSOC), Kennedy Space Center, Florida, for preparing the original documents on cleanroom protective clothing specifications for both hazardous and nonhazardous operations pertaining to the Space Transportation System (STS-Shuttle). I also want to thank Mr. James Stone of McDonnell Douglas Space Systems Corporation, Space Payload Operations Contractor (MDSSC-SPOC), Cape Canaveral Air Force Station (CCAFS), Florida, for the tabulated comparison of hazardous and nonhazardous cleanroom garment specifications obtained from miscellaneous SPOC and LSOC documents for specific areas of Shuttle operations.

It was a pleasure to be part of the working group on garment specifications and to participate in stimulating discussions with the other members of the garments review team.

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I. INTRODUCTION

Since the late sixties, semiconductor manufacturers, the aerospace industry, and critical parts assemblers have demanded ultralow particle and static dissipative apparel and accessories for cleanroom applications. Products must be protected from contaminants generated by personnel and by the clothing they wear in the cleanroom. Requirements for cleanroom garments for the prevention of spacecraft contamination have been written by individual operational groups at both Eastern and Western Test Ranges, but no standard specification has been published. The purpose of this report is to consolidate all the different garment designs and requirements into one standard which will be adopted by the spacecraft community.

Cleanrooms isolate products from the "dirty" outside environment. HEPA (high efficiency particulate air) or better filtered air is circulated through the cleanroom to provide a clean environment and remove contaminants generated within the cleanroom. Make-up air is used to maintain the cleanroom at pressures greater than surrounding "dirty" areas. Cleanroom environments are monitored on the basis of the number of particles per cubic foot of air at sizes 0.5 μm and larger, as defined in FED-STD-209 (Ref. 1). Facility design, procedures, activities, and selection of cleanroom materials are important factors in the successful operation of every cleanroom.

People and their activities within cleanrooms are the major sources of contaminants, and cleanroom garments are used to prevent people-generated contaminants from reaching products. People shed one outermost layer of skin cells every day, amounting to approximately one billion cells. These cells are approximately 33 by 44 μm in size but often fragment into substantially smaller pieces, the average size of the skin particles being about 20 μm (Ref. 2). Many of these skin particles are deposited onto clothing and laundered away. Others are removed by washing and showering, but a significant proportion are dispersed into the air. This dispersal rate varies among individuals and according to their activities, but it can be between 10^5 and 10^7 particles ≥ 0.5 μm/min, i.e., up to 10^{10} per day (Ref. 2).

II. FABRICS, DESIGN, AND CONSTRUCTION

Virtually every article of clothing worn daily by the average person is woven or knitted from yarns which have been made by twisting short fibers together in a spinning process. Unfortunately, such fabrics create lint, which cannot be tolerated in controlled atmospheres. Cleanroom garments must be constructed from fabrics woven with continuous synthetic multifilament yarns. Although such garments are inherently nonlinting, they present several other problems: electrostatic interference, environmental degradation, and worker discomfort.

The synthetic materials from which cleanroom garments are manufactured have one property in common. Without chemical modification, synthetics are electrically insulating materials or dielectrics, which can become electrostatically charged by friction. Simply by rubbing an arm against his body, a worker clad in a synthetic cleanroom garment can generate triboelectric voltages in excess of 20,000 V. The electrostatic field of the garment can destroy an electronic part either directly by a voltage surge or indirectly by imparting a charge to microcontaminants which are then electrostatically attracted to the part. Antistatic finishes applied to a garment by a launderer are ineffective, short-lived, and visually undetectable, making it difficult for a worker to select a treated garment. The optimal solution has been to weave a grid of synthetic coated, nondegradable carbon yarn into the base fabric to eliminate electrostatic discharge effects. The garment can then be identified easily by quality assurance personnel.

Cleanroom garments are exposed to a wide range of hazardous conditions. Cleanroom fabrics must be resistant to spilled chemicals, such as nitric and sulfuric acids, as well as resistant to high heat sources, hypergolic propellants, and infrequent flash fires. Polyester garments are preferred when working with chemical hazards, but nylon (Nomex) garments are chosen when fire hazards are present. The type of conductive yarn used to make the base fabric static-dissipative must be selected carefully. Nylon-coated conductive yarns are readily subject to acid attack, while metallic or dyed yarns are subject to oxidation and embrittlement, all resulting in airborne contamination from release of the conductive segment of the yarn.

Synthetic fabrics are notorious for being hot and sweaty, especially if woven very tightly for maximum microcontamination control. The solution has been for the weaver to employ very fine yarns in order to create a dense, yet very sheer material. Fabrics can be woven so tightly that particles cannot easily penetrate, but moisture vapor can be released. There are two types of continuous filament yarns: monofilament yarn and multifilament yarn. Continuous multifilament yarns are manufactured by combining numerous monofilaments during the spinning process. Garments woven from multifilament yarns contain innumerably more pores than garments woven from monofilament yarns and are therefore much more comfortable to wear for long periods of time. This is the fabric type used extensively for cleanroom apparel.

Most cleanroom garments are designed and constructed in such a way as to further control the release of particles both from the garment and from the body. The stitching is double needle, flat felled to ensure complete seam closure. Conductive thread is sometimes used along the seams to minimize electrostatic discharge (ESD) effects resulting from mismatches of conductive grid segments. Needles employed in sewing are no larger than the threads that will fill the holes. All cut edges are presurged (overcast). Zippers are especially designed to limit the number of particles escaping from the garment. Design details such as pockets, belts, tucks, and gathers are either limited or eliminated altogether. Badge pockets and safety harnesses are optional.

In the last five years one attempt to address microfiltration was the introduction of a new cloth constructed of two or three laminations. The basic material was woven polyester with an adhesively bonded outer membrane of 25-μm-thick microporous PTFE (polytetrafluoroethylene). The filtration efficiency of this cloth, called Gore-Tex[1], was measured at 0.2 to 0.3 μm, or 10 times finer than the value determined for woven multifilament polyesters (Ref. 3). This solved one major problem, but it introduced new ones. PTFE is very high on the triboelectric chart for charge potential. Also, the wear resistance to light abrasion is poor, allowing fluorine-based microparticulate contaminants into a facility. One modification was to add a top layer of finely woven polyester with static dissipative fibers. Three laminations, however, resulted in a very stiff fabric with poor vapor tranmission rates. The cost of the dual laminate fabric was about eight times greater than the cost of woven polyester.

Thintech[2] cleanroom laminates have been introduced recently by the Insulation and Specialty Fabrics division of Minnesota Mining and Manufacturing Company (3M). They are manufactured by bonding a membrane of 25% microporous polyolefin and 75% polyurethane to either a 100% polyester fabric (standard laminate) or to an 87% polyester/13% Lycra[3] fabric (stretch laminate). Because the Thintech membrane is completely impregnated with a hydrophilic polymer, cleanroom garments manufactured from this fabric offer great comfort and durability, even after 75 commercial cleanroom launderings, and high resistance to acids and a wide range of solvents. 3M also offers a Thintech Patch Tape which incorporates a heat-activated adhesive layer. The tape can be applied to tears and cuts in the garment by pressure and an ordinary hand iron or by a heat press.

Another product now being marketed for cleanroom garments, called SilverTech[4], is also made up of two layers of shielding. Woven 87% texturized polyester substrate with 13% carbon-suffused nylon monofilament in a diamond-pattern double strand is bonded to a smooth layer of microporous polyurethane impregnated with entrapped metallic nickel particles. Preliminary tests show this fabric to outrank all the others in the areas of filtration efficiency, static shielding, abrasion resistance, chemical splash resistance, and durability. Cool temperatures are required during the drying cycle after the fabric is washed, and no data exist as yet on drycleaning requirements. SilverTech is neither flame retardant nor meltproof, so cannot be used to fabricate garments for use in hazardous situations.

Trademarks: [1]W. L. Gore and Associates, Inc., [2]3M Company, [3]Dupont Company, [4]Colonial Glove and Garment, Inc.

III. DISCUSSION OF TEST METHODS

Current test methods for particle and fiber counts, for moisture vapor transmission rates, static electric-charge distribution, and identification of chemical residue, are limited to small samples of garment material or are restricted to small areas of individual garments. Many of the test methods are outdated in view of current contamination control needs. Modern barrier fabrics require entirely new test procedures because of extremely low porosity.

A. PARTICLE SIZE AND MORPHOLOGY

The traditional method for measuring particles in and on cleanroom garments, ASTM F51 (Ref. 4), dates back to 1968, with minor revisions being made in 1984. Particles and fibers are collected on a 47-mm-diameter gridded membrane filter, using an airflow of 14.0 l/min (0.5 ft^3) through the fabric. The particles and fibers are observed in an optical microscope set at 100x magnification to determine the number and morphology of all particles 5.0 μm or greater in size. Samples are collected from a sufficent number of areas on a garment to satisfy the statistical criterion that the total number of particles (N_T) counted times the number of grid squares (F_N) is greater than 500. The number of particles (or fibers) per 0.1 m^2 (1 ft^2) of fabric is then calculated from the relationship:

$$\text{Particles/0.1 m}^2 = F_N/100 \times N_T/20 \times 1/\text{Number of Sample Areas}$$

A variation of this method has been adopted by the Institute for Environmental Sciences (IES) in Recommended Practice IES-RP-CC-003 (Ref. 5). One-tenth m^2 (1 ft^2) of a garment is supported on a wire-mesh grid and vacuumed onto a membrane filter at a constant pressure differential of 10 cm (4 in.) water gage. Particle and fiber counts are determined according to the traditional method above. These two techniques have merit where particles below 5 μm in size are of no interest. Cleanroom garments showing high particle counts of sizes of 5 μm or larger may be indicative of fabric or processing system breakdown. While this standard was appropriate for fabrics having high air permeability and relatively open structure, such as herringbone and coarse twill, it is clearly outdated when evaluated against current requirements for submicron particle control. The method is almost useless for checking barrier fabrics because of low air permeability through them.

The Helmke Drum test method, developed by George Helmke of AT&T (Ref. 6), seeks to quantify 0.5-μm and larger particles. The method utilizes a process similar to that used in a clothes dryer. Garments are tumbled inside a drum rotating at 10 rpm, while the air over the tumbling garment is tested with an automatic optical or laser particle counter of the type normally used to measure airborne particles in cleanrooms. Particle counts are determined at 1-min intervals over a period of 10 min. Results are tabulated and analyzed for average, mean, and median values as a function of differing size intervals. Only within the past few years has any serious attempt been made to develop statistically significant and repeatable data on the Helmke Drum method to determine the time integrated release and size spectrum of particles from both woven and nonwoven garments down to 0.3 μm in size. A new fully automated drum tester, the RTC-2000 rotating test chamber (Ref. 7), has recently been installed in Micron-Clean Uniform Company's Class-100 garment processing facility. To make the unit suitable to a production environment, engineers at Micron-Clean developed a unique integral hollow axis which also serves as a sampling tube. This innovation allows the chamber to be connected quickly and easily to a particle counter and permits simple loading through a hinged access door (Ref. 8).

Particle removal efficiency of a garment depends primarily on pore size and air permeability of the fabric from which it is constructed. A summary of contamination control properties of certain fabrics is given in Table 1. The pore size of the holes in the fabrics was measured by the method described in British Standard 3321:1969 (Ref. 9), a bubble-point test using certain solvents. To obtain the permeability, a pressure drop of 1 cm water gage was set across a 50-mm-diameter sample of fabric, and the airflow was measured by a flow meter. This air volume was used to calculate the airflow (ml) that would pass in 1 sec through 1 cm^2 of the test fabric. Details of both procedures are described elsewhere (Ref. 2). A comparison of the pore diameter and air permeability is shown in Fig. 1, and a log/log plot of pore diameter versus particle removal efficiency is shown in Fig. 2. It is clear that, for woven fabrics, the larger the pore size, the less the efficiency of particle removal. The nonwoven PTFE laminate with large pore size and good air permeability has good particle removal efficiency because particles are trapped in the microscopic mat incorporated in their construction. As the air permeability of a fabric decreases, the effectiveness of the garment increases. If the air permeability of the garment goes below 0.5 $ml/cm^2/sec$, however, the high pressure that develops results in human particulate contaminants being pumped out of the garment at the neck, trouser, and sleeve openings. Proper design of closures on the garment can reduce particle dispersion.

One of the test methods of interest is the "body-box" or dispersal chamber test method described in IES-RP-CC-003. This test method may be used to compare relative release from different operator/garment combinations under specified activity conditions simulating typical cleanroom motions. While this is not an absolute test, since different operators disperse particles at different rates, it offers an opportunity to compare particle containment characteristics of different garment fabrics and styles under pseudo-operational conditions. It has also been widely reported that there is a gradual increase in pore size of cleanroom garments after processing, varying from fabric to fabric. It would, therefore, be advantageous to evaluate fabrics by a simulated in-use test to determine the effect of continuous processing.

B. MOISTURE VAPOR TRANSMISSION RATE

The temperature of the human body is controlled primarily through the evaporation of perspiration. In ordinary street clothing, moisture evaporates rapidly because there is abundant air movement through garments made from porous or absorbent fabrics having high air permeability. In marked contrast, filtration requirements and low linting specifications required for cleanroom garments mandate fabrics with limited air permeability and essentially no

Table 1. Contamination Control Properties of Fabrics (Ref. 2)

Type of Fabric	Pore Size (μm)	Air Permeability	Particle Removal Efficiency ≥ 0.5 μm	≥ 5.0 μm
WOVEN ARTIFICIAL FABRICS:				
Company A				
Ceramic polyester – type 1	17.2	0.10	50	98
Ceramic polyester – type 2	19.4	0.23	32	84
Antistatic nylon	66.9	4.27	7	42
Nylon	102.0	11.8	4	9
Company B				
Herringbone polyester	43.0	2.10	10	81
Company C				
Antistatic polyester 1 – grid	60.0	3.4	9	64
Company D				
Antistatic polyester 2 – strips	56.6	1.97	8	40
Antistatic polyester 3 – strips	58.0	8.50	6.3	31
Antistatic polyester 4 – grid	29.1	0.31	47	95.2
Antistatic polyester 5 – strips	17.9	0.12	49	98.1
Antistatic polyester 6 – grid	25.0	0.39	33	71
Company E				
Antistatic polyester 7 – grid	19.4	0.49	56	93.7
Company F				
Antistatic polyester 8 – grid	41.0	2.40	28	91
Antistatic polyester 9 – grid	31.6	0.71	17	81
Company G	103.0	12.3	5	28
COTTON FABRICS:				
Ventile Cotton	19.0	4.0	75	99.68
Hospital Cotton	85.0	15.0	14	32
NONWOVEN FABRICS:				
Spun-bonded nylon	129.0	25.3	20	94.5
Composite melt blown polypropylene	110.0	7.03	50	99.99
Spun-bonded polyolefin	16.0	0.02	91	99.0
PTFE laminate	<1.0	0.08	>99.99	>99.99

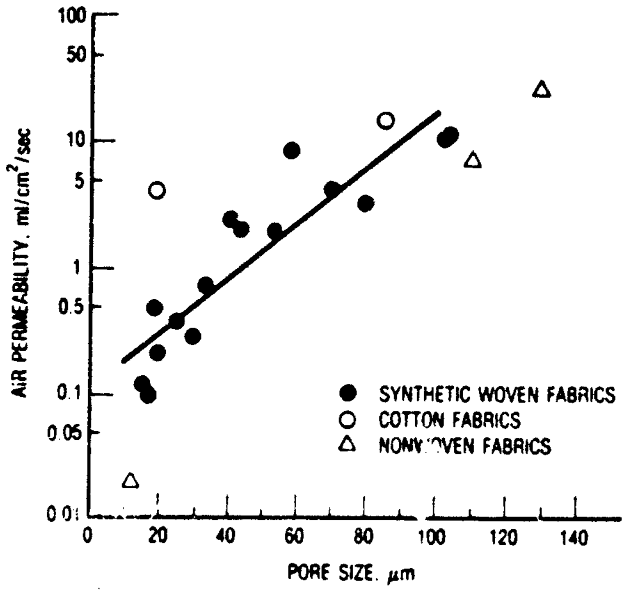


Figure 1. Air Permeability vs Pore Size

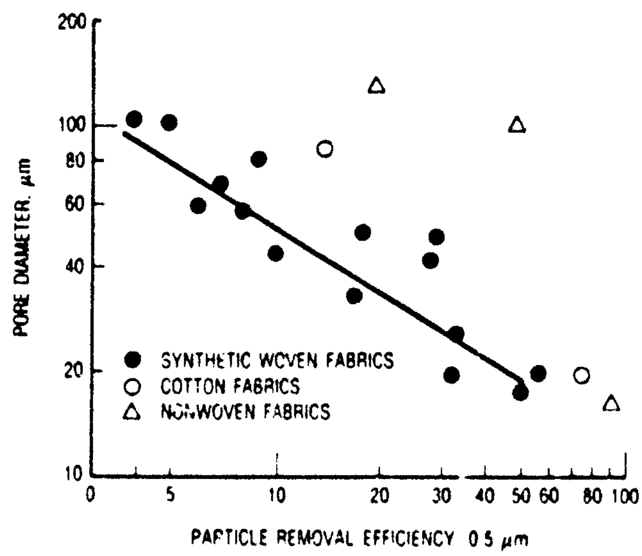


Figure 2. Pore Diameter vs Removal Efficiency ($\geq$ 0.5 μm)

absorbency. The only remaining mechanisms for moisture transfer through cleanroom garments are diffusion and capillary transfer.

There is no standard test method designed specifically for measuring the moisture vapor transmission rate (MVTR) of woven and nonwoven cleanroom fabrics. The most commonly referenced document is ASTM E96-80 (Ref. 10), which contains a summary of several test procedures applicable to sheet materials used in the construction industry as vapor barriers. The Water Vapor Permeability Cup test and the Method B (upright) test have been selected from E96 as acceptable by fabric manufacturers. It is almost impossible, however, to compare data obtained from different suppliers because of differences in the test method (vertical or upright) and environmental test conditions such as temperature, relative humidity, and barometric pressure. W. L. Gore and Associates use a proprietary dessicant moisture-recovery method which correlates well with results from the thermophysiological predictive garment models and with user experience.

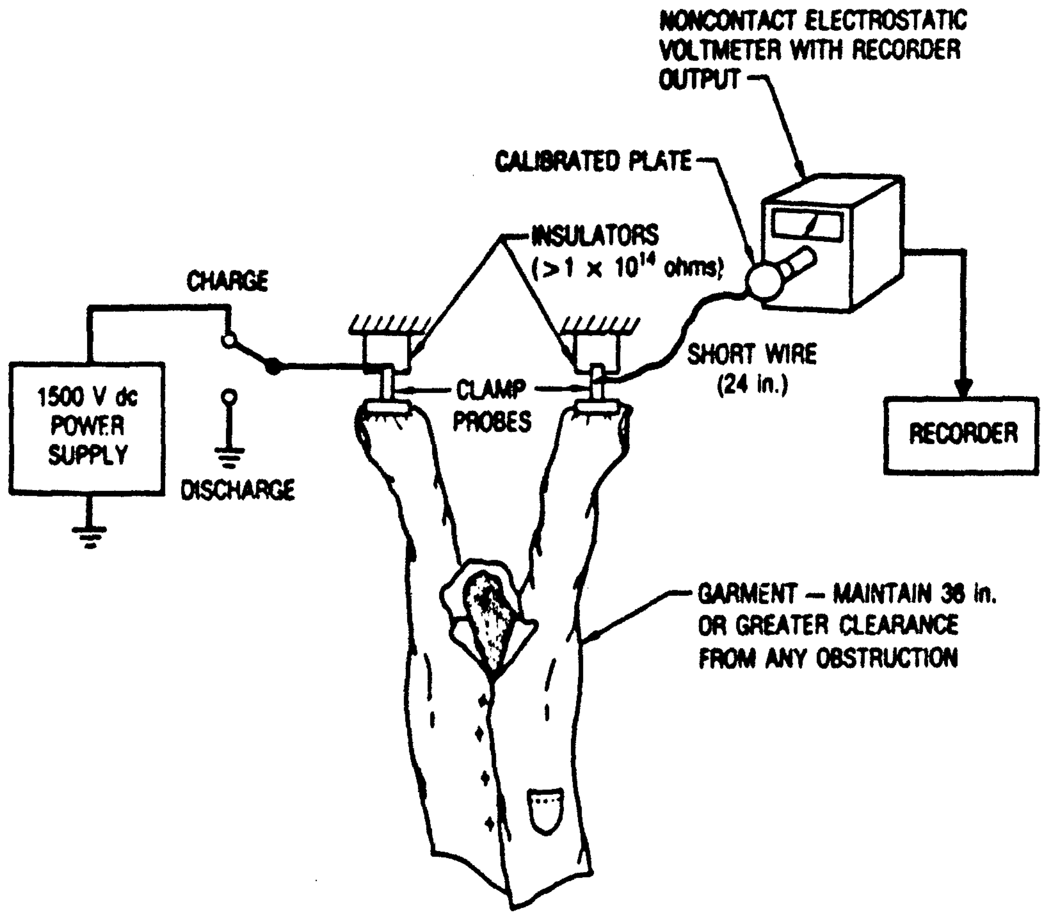
C. STATIC ELECTRICAL CHARGE

Electrostatic discharge tests are intended to ensure that garments can conduct static charges effectively to ground across the seams, do not generate triboelectric charges when friction is applied, have electrical continuity among the mechanically attached components, and have sufficient resistance for personnel safety. For all the tests described below, garments or swatches of fabric must be conditioned in a dessicating chamber or controlled humidity room for 24 hr at 20% ± 2% RH (relative humidity) prior to testing, and all static control tests must be conducted at 20% ± 2% RH and 20° ± 0.5°C (68° ± 0.9°F).

A surface resistivity test at controlled humidity, ASTM D257 (Ref. 11), may be used for routine monitoring of similar fabrics or garments. In this method a concentric ring electrode, the IKE-probe, is used in conjunction with a high resistance (10^4 to 10^{14}) ohmmeter to obtain resistivities. Volume resistance can be measured by placing a single layer of coverall material between a nonoxidizing metal plate, 20 x 50 cm (8 x 20 in.), and a 2270-gm (5-lb) weight per NFPA 99 (Ref. 12). A calibrated megohmmeter having an open-circuit output voltage of 50 Vdc is used to measure resistance at four different places on the garment. The average value should be greater than 2.5×10^5 ohms but less than 1×10^9 ohms to be acceptable. Resistivity measurements are good for comparative testing, but neither of the above methods can be used to describe accurately the antistatic properties of apparel. Repeatability and accuracy of the results are affected by moisture content, surface irregularities, properties of the interwoven conductive fibers, and residual chemicals on the fabric.

In Federal Test Method Standard 101C, Method 4046 (Ref. 13), fabric samples are charged alternately to +5000 and -5000 Vdc and grounded in a special fixture. Static voltage decay is recorded on a chart recorder or storage oscilloscope.

The Electrical Overstress/Electrostatic Discharge Association has proposed a method of measuring static decay for entire cleanroom outfits (tentative EOS/ESD Standard 11). The test setup is illustrated in Fig. 3, and the method is described in AGMC/MAQC-335c (Ref. 14). For this measurement of ESD, an entire garment is suspended from insulated test clamp



CLAMP PROBES MAY BE SUSPENDED FROM INSULATORS 6 in. TO 36 in.
APART AS APPROPRIATE TO GARMENT SIZE

Figure 3. Typical Static Voltage Decay (Dissipation) Test Setup (Ref. 14)

probes in free space with 3 ft of clearance on all sides. A noncontacting electrostatic voltmeter is attached and calibrated to read the voltage on one of the clamp probes. A charge of 1500 Vdc is applied to the other clamp probe until the garment is fully charged. The decay value is obtained by measuring the time from closure of the grounding switch to 10% of the initial charge. If static decay time is not equal to 2 sec or less, there may be a lack of continuity of the conductive filament grids at the garment seams, destroying the Faraday cage shield performance of the garment. This situtation might be remedied by constructing the garment with conductive thread at all seams. The continuity of the cleanroom garment, together with the booties, can be tested in a similar manner, illustrated in Fig. 4. Again, if static decay time is not equal to 2 sec or less, there may be a lack of continuity of the conductive filament grids either at the seams of the garment or at the junction of the bootie and the coverall. The test should be repeated after conductive tape is applied to the top of the bootie/coverall junction.

The ability of a fabric to generate static-charge triboelectrically is dependent on many factors, and repeatable test results are difficult to produce. One of the simplest test procedures is to rub briskly two areas of the test article with a 12.5 x 12.5 x 5 cm (5 x 5 x 2 in.) Teflon[5] (PTFE) block and to measure the resultant triboelectric voltage within 30 sec afterward. A noncontact electrostatic probe must be used for scanning, and is held at a distance of 9.5 to 12.5 mm (3/8 to 1/2 in.) away from the garment. The test setup is illustrated in Fig. 5. The first test area of the garment is scanned for 30 sec, and a corresponding recorder trace from the output of the voltmeter is taken. This procedure is repeated two more times. For a garment to be acceptable, the measured voltage shall not exceed 150 V at any point on each of the three traces.

Better control and improved accuracy in the determination of triboelectric voltage is possible using the rotating PTFE wheel test fixture developed by NASA, Kennedy Space Center (Ref. 15), with a voltmeter, memory chart recorder, and digital memory recorder or a digital oscilloscope and camera to record initial voltage and voltage decay characteristics as a function of time. The NASA test fixture is designed to allow a 17.5 x 19 cm (7 x 7.5 in.) preconditioned sample of fabric to be rubbed for 10 sec by a convex PTFE disk rotating at 400 rpm, ± 20 rpm. When the disk is retracted, the sample holder simultaneously rotates through 90 deg to present the sample to the electrostatic voltmeter, while a microswitch provides a zero time marker signal to the recorder or to the oscilloscope.

D. CHEMICAL RESIDUE

Ionic contaminants residing on cleanroom garments are of particular interest to the semiconductor community. The major anions (-) of concern are chloride, phosphorous, and sulfate ions. Cations (+) which must be eliminated from garments include sodium, potassium, lithium, aluminum, boron, and arsenic. The standard method for measuring free ionic residues on garments involves liquid solvent extraction followed by atomic absorption spectroscopy of the cation and colorimetric or turbidimetric analysis for the anions (Ref. 16). Responsibility for removal of these contaminants lies with the garment processor through the use of acceptable chemical cleaning formulations and rinsing cycles.

[5]Trademark of DuPont Company

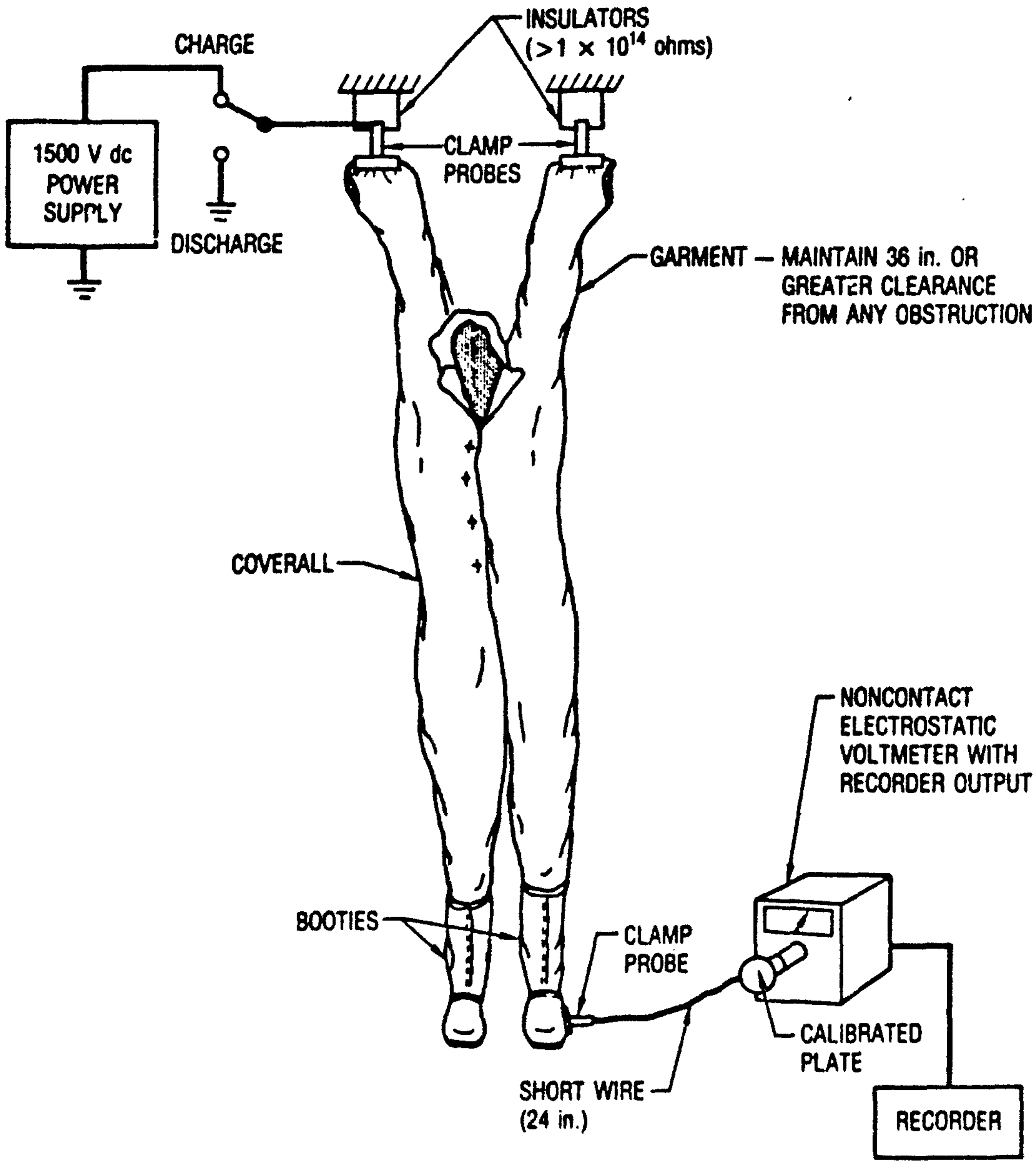


Figure 4. Coverall and Bootie Continuity Test Setup (Ref. 14)

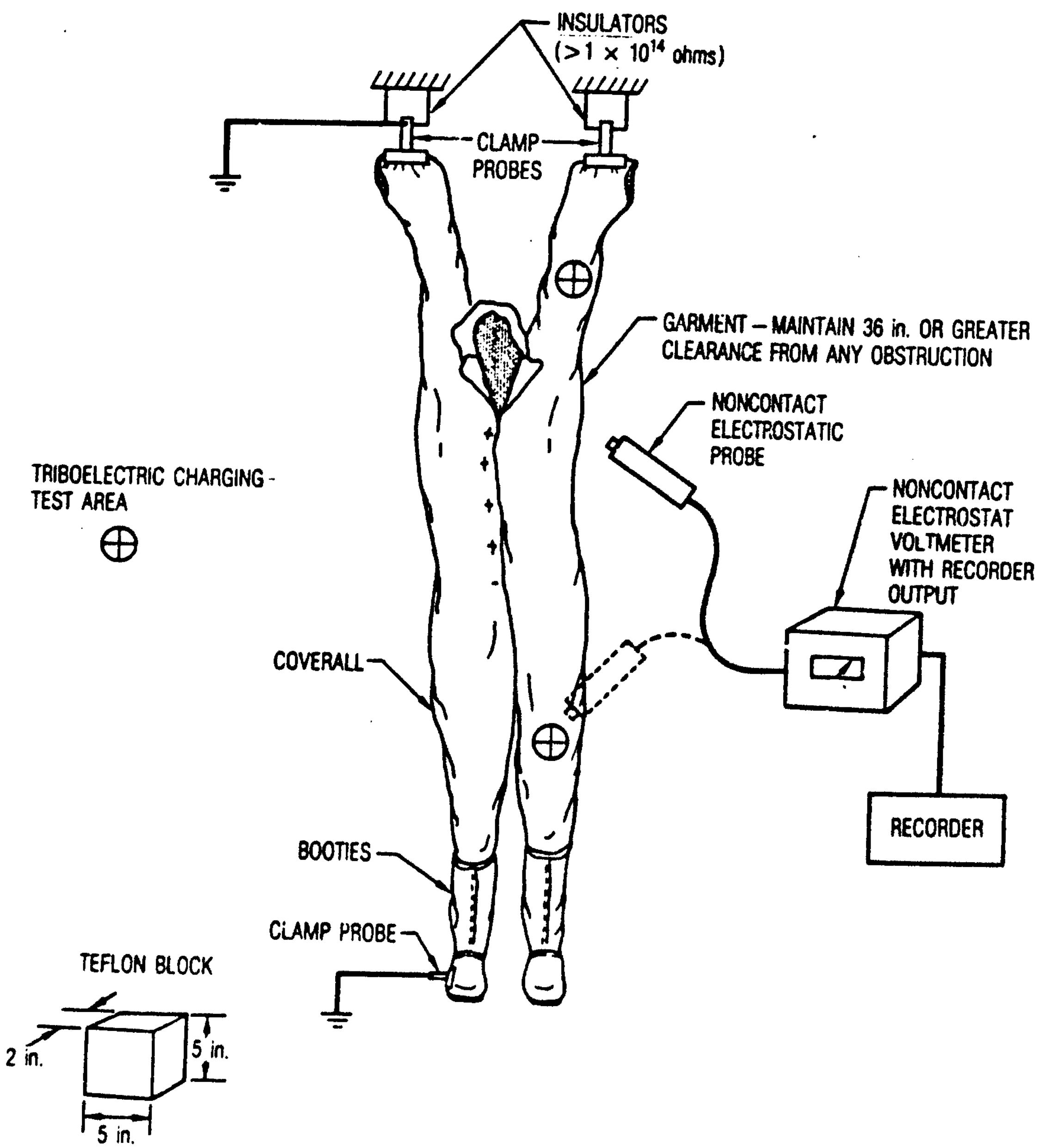


Figure 5. Triboelectric Charging Test Setup (Ref. 14)

IV. SELECTION OF GARMENT ELEMENTS

Selection of elements of the cleanroom garment should be governed by the dual objectives of preventing the release of people-generated particles and particles from the garments into the environment. The most effective garment ensemble for preventing people-generated particles from getting into the cleanroom environment is totally sealed and has a supply of breathing air.

The attached garment specification (Appendix A) is a compromise involving product cleanliness requirements, personnel comfort, usability, and cost. More stringent requirements will dictate greater attention to particular issues. Each product should be reviewed to determine the appropriate cleanliness requirements during each phase of the manufacturing process.

Two types of cleanroom garments are specified as "hazardous" and "nonhazardous." Both types of garments are intended to meet the NFPA (Ref. 17) minimum safety requirements with respect to flammability, compatibility with solvents and some liquid propellants, control of electrostatic discharge, and other general safety issues for cleanroom garment ensembles.

The garment ensemble specified for hazardous use provides some additional protection to the wearer from exposure to flames that the nonhazardous polyester garment does not provide. Polyester fabric can produce melt burns on the wearer if the garment is exposed to temperatures in excess of 250°C (480°F). The synthetic aromatic nylon polymeric fiber of which Nomex is woven is not only flame retardant but meltproof as well. It is the responsibility of the user to select the garment that will meet the necessary safety requirements. If a known fire hazard exists, Nomex should be the garment of choice.

Hoods and Face Masks

Hoods and face masks are considered to be a minimum requirement for the protection of products from personnel in close proximity. Snoods that cover only the hair are generally not acceptable because there is an increase in the risk of people-generated contaminants reaching the product.

Gloves

Although gloves are not included in the specification, enclosing the hands and garment cuffs in an appropriate glove is essential for personnel working near to or touching sensitive hardware. Powderless latex gloves are typically used. Polyester and nylon woven gloves are acceptable for some applications. Wearer comfort and the ability of personnel to perform the required tasks also enter into the decision of when and where gloves should be required.

Shoe Covers and Cleanroom Booties

The only effective method of preventing contaminants from falling out of the trousers of the coverall is to enclose the lower end of each pant leg in a high-top cleanroom bootie. Shoe covers that do not contain the pant legs have limited value.

The bootie design is important not only for contamination control, but also for worker safety. Booties that do not provide a secure anchor for the foot because of shoe slippage within the bootie or slippage between the bootie and the floor can be a safety hazard. The selection of the material used for the sole of the bootie is also important for contamination control. Some materials show excessive wear and abrasion, thereby generating particles within the cleanroom.

V. SUMMARY

Contamination from workers and from clothing can destroy the effectiveness of critical space hardware. Special fabrics, uniquely constructed cleanroom garments, and processing of soiled garments to rigid specifications are needed to avoid contaminating sensitive surfaces. Specifications for hazardous and nonhazardous cleanroom garments have been written by many different operational groups at both Western and Eastern Test Ranges, but no formal documentation has been published, and little agreement can be found among the different specifications. The purpose of this report is to consolidate all the different garment designs and requirements into one standard specification for garments required in cleanrooms and controlled environments for spacecraft for nonhazardous and hazardous operations.

The information in Appendix A has been submitted to committee E-21 (Ref. 18) for consideration as an ASTM (American Society for Testing Materials) standard. Standards are used as a guide to uniformity in the industry. They are not meant to be static documents, and are reviewed and updated periodically as new materials become available and new requirements are imposed.

New concepts in nonhazardous cleanroom garments include materials that are made of microporous polyurethanes bonded to woven polyester in which a carbon-suffused nylon monofilament is incorporated for ESD protection. Worker comfort and improved filtration efficiency are some of the advantages of this type of material and construction. No replacements for the Nomex flame-resistant fabric for hazardous garments have been found as yet, but research is continuing to find substitutes offering even greater protection from fires, more comfort, and improved contamination control.

Current methods and procedures for testing and evaluating cleanroom garments need to be updated to include modern barrier fabrics. Priority needs to be given to standardizing complete garment and garment/operator system test procedures, using automatic test equipment wherever possible, to facilitate routine in-service evaluation of contamination levels.

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3. L. Hertzon, "Garments Go to High-Tech Designs to Meet Needs of Today's Cleanrooms," *Cleanrooms*, September 1988.

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6. R. D. Beeson, "Everything You Always Wanted to Know About Cleanroom Garments...," *Cleanrooms*, September 1989.

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10. ASTM E-96-80, *Test Methods for Water Vapor Transmission of Sheet Materials.*

11. ASTM D257, *Test Methods for DC Resistance or Conductance of Insulating Materials.*

12. NFPA 99, *National Specifications on Health Care Facilities, 1984.*

13. Federal Test Method Standard 101C, Method 4046.1: *Electrostatic Properties of Materials.*

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15. E. S. Burnett and C. W. Berndt, "Static Electrical Charge and Chemical Residue Garment Testing Do Not Measure Up," *Cleanrooms*, January 1989.

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17. NFPA: National Fire Protection Association Standard 702-1980 for Fire Retardation.

18. ASTM E-21 Committee on Space Simulation and Applications of Space Technology.

APPENDIX A
STANDARD SPECIFICATION FOR GARMENTS REQUIRED IN CLEANROOMS AND CONTROLLED ENVIRONMENTS FOR SPACECRAFT FOR HAZARDOUS AND NONHAZARDOUS OPERATIONS

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1. Scope

1.1 This document covers specifications governing the selection of special items of clothing designed to protect products from contaminants released by personnel and garments. Special clothing includes coveralls, footwear, and head covers.

1.2 *This specification may involve hazardous materials, operations, and equipment. This specification does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this specification to establish appropriate safety and health practices and determine applicability of regulatory limitations prior to use.*

1.3 The values stated in SI units are to be regarded as the standard.

2. Referenced Documents

2.1 ASTM Standards:

D 123-82a, Standard Definitions of Terms Relating to Textiles

D 204-82(1986), Standard Methods of Testing Sewing Threads

D 1683-81, Standard Test Method for Failure in Sewn Seams of Woven Fabrics

D 1894-78(1986), Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting

D 4157-82, Test Method for Abrasion Resistance of Textile Fabrics (Oscillatory Cylinder Method)

E 96-80, Test Methods for Water Vapor Transmission of Materials

E 1235-88, Standard Test Method for Gravimetric Determination of Non-volatile Residue (NVR) in Environmentally Controlled Areas for Spacecraft

F 24-65(1983), Method for Measuring and Counting Particulate Contamination on Surfaces

F 51-68(1984), Standard Method for Sizing and Counting Particulate Contamination In and On Clean Room Garments

F 312-69(1980), Method for Microscopical Sizing and Counting Particles from Aerospace Fluids on Membrane Filters

2.2 U.S. Federal Standards:

FED-STD-101B, Electrostatic Properties of Materials

FED-STD-191, Textile Test Method

FED-STD-209D, Clean Room and Work Station Requirements, Controlled Environment, June 1988

FED-STD-751a Stitches, Seams, and Stitchings

2.3 U.S. Military Standards:

MIL-STD-105D, Sampling Procedures and Tables for Inspection by Attributes

MIL-STD-1246B, Product Cleanliness Levels and Contamination Control Program, 4 September 1987

MIL-C-43122E, Cloth, Sateen, Cotton, Flame Retardant Treated

MIL-C-85043A, Cloth, Cleaning, Low Lint

2.4 Other Publications:

AGMC/MAQC-335c, Electrostatic Discharge (ESD) Requirements for the Protection of ESD Sensitive Items: Personnel Garments, 22 February 1989

IES-RP-CC-003-87-T, Recommended Practice, Garments Required in Cleanrooms and Controlled Environment Areas

NASA Handbook, NHB 8060.1B, Test 1

NASA/KSC GP-1098, STS Safety, Reliability, and Quality Assurance Ground Safety Plan, Launch Complex 39, KSC Industrial Area

NASA/KSC Materials Testing Branch Report MMA-1985-79

NASA/KSC Materials Testing Branch Report MTB-066-72

National Fire Protection Association Pamphlet 77

National Fire Protection Association Standard 702-1980

U.S. Air Force, Space Systems Division, Technical Report SD-TR-89-63, Standard Method for Measurement of Nonvolatile Residue on Surfaces, E.N.Borson, E.J.Watts, G.A.To.

U.S. Air Force T.O. 00-25-203, Contamination Control of Aerospace Facilities, U.S. Air Force, 1 December 1972, Change 12, 30 December 1989

3. Definitions

3.1 bungie cord—6-mm (1/4-in.)-diameter strip of elastic cord covered with fabric, similar to a garter, and often having hooks attached to both ends.

3.2 bunny suit—complete cleanroom outfit consisting of coverall, shoe covers, and headwear. Wearer resembles a large white rabbit when fully suited.

3.3 cleanroom—an enclosed area employing control over airborne particles, temperature, humidity, molecular species, pressure, activities, and other environmental parameters that may be required to produce acceptable products. HEPA filters are required for the incoming air, and the maximum allowable particulate environment under operational conditions is Class 100,000 per FED-STD-209D.

3.4 count—in woven textiles, the number of warp yarns (ends) and filling yarns (picks) per unit distance as counted while the fabric is held under zero tension and is free of folds and wrinkles.

3.5 Delrin—DuPont trade name for a crystalline form of polymerized formaldehyde.

3.6 denier—a unit of mass for measuring the fineness of threads of silk, rayon, nylon, etc., equal to 0.05 g per 450 m.

3.7 drycleaning—nonaqueous solvent cleaning. Solvent is usually perchloroethylene.

3.8 end—an individual warp yarn (single or ply) or cord.

3.9 extractable matter—the nonfibrous content of a textile extractable by solvents and water, usually oils, greases, and resins.

3.10 fabric, woven—a planar structure produced by interlacing two or more sets of yarns, fibers, rovings, or filaments where the elements pass each other essentially at right angles and one set of elements is parallel to the fabric axis.

3.11 fiber—a particle with a length-to-width ratio of at least 10 to 1.

3.12 filament—a variety of fiber having extreme length, not readily measured. Synthetic fibers formed from man-made and natural polymers are in this class.

3.13 flame resistance—the property of a material whereby flaming combustion is prevented, terminated, or inhibited following application of a flaming or nonflaming source of ignition, with or without subsequent removal of the ignition source. Textiles are tested in accordance with the National Fire Protection Association Standard 702-1980, under the classification of wearing apparel.

3.14 float—the portion of a warp of filling yarn that extends unbound over two or more filling or warp yarns.

3.15 hazardous—of or involving danger of loss or injury resulting from exposure to a potentially flammable environment.

3.16 HEPA—high efficiency particulate air filter. A throw-away extended-media, dry type filter in a rigid frame having a minimum particle collection efficiency of 99.97% for 0.3-μm particles, and a maximum clean-filter pressure drop of 25 mm (1.0 in.) water gauge, when tested at rated airflow capacity.

3.17 lint—fiber fragments abraded from textile materials; also loose short fibers or fluff.

3.18 Nomex—a synthetic aromatic nylon (Aramid) polymeric fiber manufactured by DuPont for applications requiring good dimensional stability and excellent heat and flame resistance.

3.19 nylon—a generic term for any long-chain synthetic polymeric amide which has recurring amide groups as an integral part of the main polymer chain, and which is capable of being formed into a filament in which the structural elements are oriented in the direction of the fiber axis.

3.20 particle—a piece of material which is observable to have length, width, and thickness.

3.21 ply—the number of single yarns twisted together to form a plied yarn; also the number of plied yarns twisted together to form a cord.

3.22 polyester—a polymer in which the fiber-forming substances are an ester of dihydric alcohol and terephthalic acid.

3.23 porosity—the ratio of the volume of air or void contained within the boundaries of a material to the total volume (solid matter plus air or void) expressed as a percentage.

3.24 sewn seam—a juncture of which two or more planar structures, such as textile fabrics, are joined by sewing, usually near the edge.

3.25 static dissipative fabric—an inherently static control fabric with surface resistivity between 10^5 ohms per square and not more than 10^9 ohms per square.

3.26 stitch—the repeated unit formed by the sewing thread in the production of seams in sewn fabric.

3.27 surface resistivity—a measure of the electrical conductivity of a material.

3.28 twill weave—a weave characterized by diagonal lines produced by a series of floats staggered in the warp direction. Floats are normally formed by the filling.

3.29 warp—the yarn running lengthwise in a woven fabric.

3.30 water-wash machine cleaning—a process in which garments can be washed, bleached, dried, and pressed by any customary home or commercial method.

3.31 yarn—a generic term for a continuous strand of textile fibers, filaments, or material in a form suitable for knitting, weaving, or otherwise intertwining to form a textile fabric.

3.32 yarn number—a measure of the fineness or size of a yarn expressed either as mass per unit length (direct system) or as length per unit mass (indirect system). The kg/m (denier) system is a direct one, and denotes the linear density of the yarn.

4a. Garment Requirements, Nonhazardous

4a.1 Flame Resistance: garments in this category should be flame retardant but not necessarily melt proof. Must meet NFPA Standard 702-1980 for fire retardancy.

4a.2 Fabrics: all fabrics of which garments are made shall be low linting in order to minimize airborne particulate contamination in cleanrooms.

4a.3 Yarn: 99% continuous filament Dacron polyester with 1% raised grid carbon/polyester filament yarn, 100% multifilament.[1]

4a.4 Thread count: warp of 172 ± 2 ends/25 mm, fill of 82 ± 2 ends/25 mm.

4a.5 Weave: 2/1 twill with 6.5-mm (1/4-in.) raised grid of 1% carbon/polyester and 99% Dacron polyester filament.

4a.6 Weight: 102 ± 5 g/m^2 (3.00 ± 0.15 oz/yd^2)

4a.7 Permeability: 6.6 ± 1.9 cm3/sec (14 ± 4 cfm) per FED-STD-191, Method 5450 (Frazier Test).

4a.8 Tensile Strength: warp of 41 kg (90 lb) minimum, fill of 23 kg (50 lb) minimum per FED-STD-191, Method 5104 (Ravelled Strip).

4a.9 Static Dissipation: fabric must meet the NASA/KSC GP-1098 static dissipation requirements both initially and after cleaning. Voltage must drop to 10% or less of the applied voltage within 5 sec and below 350 V in 5 sec at 25 + 5% maximum relative humidity and 24°C (75°F) maximum temperature.

4a.10 Extractables: less than 0.5% NVR by fabric mass. Analytical procedures for determining extractable residues from cloths are described in SD-TR-89-63. The test method described in ASTM E 1235-88 may also be used provided the 0.1 m^2 (1 sq ft) stainless steel sample is replaced by a piece of fabric of equivalent size.

4a.11 Linting Characteristics: must meet ASTM F51-68(1984) Class A requirements for cleanroom operations.

4a.12 Shrinkage: less than 1% at 120°C (250°F) for 1/2 hr in dry heat, in a relaxed condition.

4a.13 Color: as specified by the user. Laundering shall not result in discoloration.

4b. Garment Requirements, Hazardous

4b.1 Hazardous: garments in this category must be compatible with combustibles such as fuels and oxidants which might ignite.

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[1]Chemstat 909 (Stern & Stern), Selguard II (Teijun, Japan), C3 (Burlington/Klopman Fabrics), ASQ-100 and Cubic 10 (Angelica Uniform Co.) have been found to be satisfactory. Other acceptable fabrics may also be available.

4b.2 Fabrics: all fabrics shall be low linting in order to minimize airborne particulate contamination in cleanrooms. Fabric must be flame retardant, melt proof, and must meet or exceed the requirements of NASA Handbook NHB 8060.1B, Test 1, for flame retardancy.

4b.3 Yarn: 99% continuous filament Nomex, with 1% carbon-conjugated conductive nylon filament yarn, 100% filament, mass of 10g/450 m (200 denier).[2]

4b.4 Thread count and width: warp of 101 ±2 ends/25 mm, fill of 75 ± 2 ends/25 mm, width of 180 ± 1 cm (70.5 + 0.5 in.).

4b.5 Weave: 2/2 twill with 6.5-mm (1/4-in.) raised grid of 1% carbon/polyester copolymer and 99% Nomex filament.

4b.6 Weight: 170 ± 10 g/m^2 (5.0 + 0.3 oz/yd^2), minimum 135 g/m^2 (4 oz/yd^2).

4b.7 Permeability: 4.72 ± 2.35 cm^3/sec (10 ± 5 cfm) per FED-STD-191, Method 5450 (Frazier Test).

4b.8 Tensile Strength: warp of 86 kg (190 lb) minimum, fill of 52.5 kg (116 lb) minimum per FED-STD-191, Method 5104 (Ravelled Strip).

4b.9 Static Dissipation: fabric must meet the NASA/KSC GP-1098 static dissipation requirements both initially and after repeated cleanings during the lifetime of the garment. Voltage must drop to 10% or less of the applied voltage within 5 sec and below 350 V in 5 sec at 25 ± 5% relative humidity (maximum) and 24°C (75°F) maximum temperature.

4b.10 Extractables: less than 0.5% NVR by fabric mass. Analytical procedures for determining extractable residues from cloths are described in SD-TR-89-63. The test method described in ASTM E 1235-88 may also be used provided the 0.1 m^2 (1 sq ft) stainless steel sample is replaced by a piece of fabric of equivalent size.

4b.11 Linting Characteristics: must meet ASTM F51-68(1984) Class A requirements for cleanroom operations.

4b.12 Shrinkage: less than 1% at 120°C (250°F) for 1/2 hr in dry heat, in a relaxed condition.

4b.13 Color: white.[3] Laundering shall not result in discoloration.

4b.14 Combustibility: fabric shall have an average time after flame of not more than 2.0 sec and an after-glow time of not more than 6.0 sec. Not more than 40% of a 2.5 x 25 cm (1 in. x 10 in.) test sample shall be consumed both initially and after 15 launderings (MIL-C-43122E and FED-STD-191, Method 5903). Boot soles must self-extinguish before 15 cm (6 in.) of material are consumed. Sparking, sputtering, or dripping of

[2] Chemstat 919 (Stern & Stern) has been found to be satisfactory.
[3] At this time only white is available. However, other colors are acceptable if the other requirements of this specification are satisfied.

flaming particles is not acceptable. Test method 1 of NASA Handbook NHB 8060.1B shall be used.

4b.15 Compatibility: fabric shall not react exothermally with fuels, oxidizers, solvents, acids, or other chemicals routinely used at aerospace component processing facilities. Examples of these substances are hydrogen, nitrogen tetroxide, hydrazine, nitric acid, sulfuric acid, hydrogen peroxide, alcohol, methyl ethyl ketone, acetone, and Freon 21.

5a. Construction Details, Nonhazardous

5a.1 Apparel worn in environmentally controlled facilities must meet specifications listed in U.S. Air Force T.O. 00-25-203, paragraph 8.3.a.

5a.2 Sewing Thread: continuous filament Dacron polyester throughout the garment. Garments must be sewed with "pre-set" threads having the same or lower rates of shrinkage than the fabric. Must meet ASTM D 204-82(1986). Conductive thread of carbon-conjugated conductive nylon filament yarn may be used at the seams to maintain whole garment continuity.

5a.3 Seams and Edges: all seams to be finished completely. Major garment seams to be double-needle flat felled following FED-STD-751A seam type LSC-2 and stitch type 401, 6.5-mm (1/4-in.) gauge. Raw edges at neck, wrist, and ankle hems must either be serged (overcast) with polyester thread, stitch type 504, or bound with fabric before joining to any other part or being hemmed. Seams must meet ASTM D 1683-81 standards.

5a.4 Entrapment Areas: pockets, belts, pleats, fold-over collars, and folded or trough cuffs are not acceptable. Other entrapment areas such as sewn-on emblems, logos, and pen-tabs are prohibited.

5a.5 Garment Identification Labels: garment shall have a label sewn inside the garment at the neck, denoting size, date of manufacture, manufacturer's name, and fabric type. Labels may be applied using a gas sublimation transfer technique which dyes the polyester yarn and produces no particles.

5a.6 Personnel Identification Labels (optional): a 5-in.-square badge pocket made of a double layer of transparent polyester mesh[4] may be sewn on the front of the coverall, 150 mm (6 in.) below the shoulder seam and 75 mm (3 in.) to the left of the zipper placket. A self-locking polyacetate zipper on polyester tape shall be used to close the top of the pocket, and a double-layered polyester flap shall cover the zipper. Badges are useful for identification purposes when large groups of workers are clad in bunny suits. Badge pocket detail is shown in Fig. A.1.

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[4]Chemstat 929 (Stern & Stern) polyester mesh fabric from Burlington/Klopman and Teijin has been found to be satisfactory. Other acceptable fabric may also be available.

5a.7 Safety Harnesses (optional): harnesses shall be manufactured from polyester and cut with a hot knife to seal erds. Straps shall be 40 mm (1-1/2 in.) wide and shall be able to withstand a pull of 900 N (200 lbf).

5a.8 Fasteners (optional): snaps, grippers, or Velcro are not recommended on any part of cleanroom protective clothing. Zipper tapes must be woven from continuous filament polyester yarns. Zipper teeth must be fabricated of a synthetic polyacetate.

5a.9 Health: garment must be comfortable, must not irritate, react with, or be abrasive to the skin, and must not emit objectionable odor when wet or dry. Pore size and air permeability affect comfort. A measure of the moisture vapor transmission rate for sheet materials is given in ASTM E 96-80.

5a.10 Sizes: choice of sizes shall be made from measurements listed in Tables I and II of this specification.

5b. Construction Details, Hazardous

5b.1 Apparel worn in environmentally controlled facilities must meet specifications listed in U.S. Air Force T.O. 00-25-203, paragraph 8.3.a.

5b.2 Sewing Thread: continuous filament flame-resistant Nomex aramid or equal throughout the garment. Garments must be sewed with "pre-set" threads having the same or lower rates of shrinkage than the fabric. Thread must meet ASTM D 204-82(1986) standards. Conductive thread of carbon-conjugated conductive nylon filament yarn may be used at the seams to maintain whole garment continuity.

5b.3 Seams and Edges: all seams to be finished completely. Major garment seams to be double-needle flat felled following FED-STD-751A seam type LSC-2 and stitch type 401, 6.5-mm (1/4-in.) gauge. Raw edges at neck, wrist, and ankle hems must either be serged (overcast) with Nomex yarn, stitch type 504, or bound with fabric before joining to any other part or being hemmed. Use of Humisal, part No.1A33 (edge lock) on fabric edges to facilitate garment handling is permissible. Seams must meet ASTM D 1683-81 standards.

5b.4 Entrapment Areas: pockets, belts, pleats, fold-over collars, and folded or trough cuffs are not acceptable. Other entrapment areas such as sewn-on emblems, logos, and pen-tabs are prohibited.

5b.5 Garment Identification Labels: each garment shall have a label sewn on the inside of the garment at the neck, denoting size, manufacturer's name, date of manufacture, and the word Nomex to indicate that the fabric is flame resistant and is for hazardous use.

5b.6 Personnel Identification Labels: a 5-in.-square badge pocket made of a double layer of transparent polyester mesh[5] may be sewn on the front of the coverall, 6 in. below the

[5]See Footnote 4.

shoulder seam and 3 in. to the left of the zipper protective flap. A self-locking Delrin zipper on polyester tape shall be used to close the top of the pocket, and a protective flap of Nomex shall cover the pocket zipper. Badge pockets shall be optional. Badges can, however, be quite useful for identification purposes when large groups of workers are clad in bunny suits. Badge pocket detail is illustrated in Fig. A.1.

5b.7 Safety Harnesses: green Nomex grab straps suitable for rescue purposes shall be sewed securely on the legs, torso, shoulders, and back of the coverall, as shown in Fig. A.2.

5b.8 Fasteners: snaps, grippers, or Velcro are not permitted on any part of cleanroom protective clothing. Zipper tapes must be woven from continuous-filament polyester yarns. Zipper teeth must be fabricated of a synthetic polymer such as Delrin.

5b.9 Health: garment must be comfortable, must not irritate, react with, or be abrasive to the skin, and must not emit objectionable odor when wet or dry.

5b.10 Sizes: choice of sizes shall be made from measurements listed in Tables I and II of this specification.

6. Design of Body Coverings

6.1 Coveralls: a full length self-locking zipper shall be used to close the main body of the coverall, and a protective placket of fabric shall be sewn to the garment along the length of the zipper. The collar shall be military style. Monofilament 100% polyester knit cuffs incorporating an antistatic 6.5-mm (1/4-in.) carbon filament grid shall be sewn at the wrist to provide positive closure. The fabric shall be doubled over before stitching to the garment and shall be sewn to the garment in such a way that both the carbon grids of the cuff and garment overlap to provide maximum static dissipation. Finished cuffs shall measure 75 mm (3 in.) long by 80 mm (3-1/4 in.) wide. There shall be no leg closures. Coveralls are illustrated in Figs. A.3 and A.4.

6.2 Headwear

6.2.1 Hoods: hoods shall fit over the head and cover all but the eyes, nose, and mouth. The fabric shall drape over the front and back of the upper body, but not over the shoulders. A 25-mm (1-in.)-wide elastic band shall be sewn inside the hood behind the neck for good fit. A detachable or disposable breathing mask shall be attached to the hood to cover all exposed facial regions except the eyes. The portion left open for the eyes shall be wide enough to accommodate prescription or safety glasses. The mask shall be made of polyester mesh having a permeability of 165 cm^3/sec (350 cfm) and a density of 50 g/m^2 (1.5 oz/yd^2).[6] A label denoting size, manufacturer, date of manufacture, and fabric type shall be sewed to the underside of the front panel of the hood. Figures A.1 and A.5 are illustrations of headwear.

[6]See Footnote 4.

6.2.2 Snoods: caps shall fully cover only the hair and ears and not the face. Snoods shall have an elastic band sewn across the back and along the sides to allow one size to fit all. Snoods have only limited use and are not recommended for environmentally controlled areas for spacecraft processing.

6.3 Footwear

6.3.1 High-Top Booties: booties shall cover the calf of the leg and extend to just below the kneecap, a nominal 18–20 in. A self-locking polyacetate zipper shall be sewn to the back and shall extend from the sole to the top of the boot. A pull-tab on the zipper inside the heel of the boot shall be added to assist in donning the boot. This tab shall be made from polypropylene webbing, folded over to form a loop. The top of the boot shall be secured with a bungie cord which shall run through the top hem of the boot. One end of the bungie cord shall be fixed to the top hem of the boot, while the other end shall run through a sliding catchment to adjust the cord tension. A polyacetate barrel lock has been found to be satisfactory. The bottom of the boot shall be secured with an interior bungie cord which shall run over the instep and around behind the ankle. Both ends of the cord shall run through a fixed polyester lock for adjusting cord tension. Exterior cords or straps are unacceptable. The soles of the booties shall be continuous, nongrooved, and extend at least 25 mm (1 in.) up on all sides. The sole shall be made of a nonskid material having a kinetic coefficient of 1.45 outside, 1.25 inside, or greater, per ASTM D 1894-78(1986). The sole material shall meet the KSC static dissipation requirements. Voltage must drop to 11% or less of the applied voltage within 5 sec and below 350 V in 5 sec at 25 ± 5% relative humidity (maximum) and 24°C (75°F) maximum temperature, per NASA/KSC MTB Report MMA-1985-79.[7] The boot size, manufacturer, date of manufacture, and fabric type shall be indicated on a small polyester label sewn into each boot at the front top of the leg. The words "left" or "right" on the label shall be optional. Shoe covers and booties are illustrated in Figs. A.2 and A.5.

6.3.2 Shoe Covers: covers shall completely cover the shoe. They shall be secured at the ankle by a 12.5-mm (1/2-in.)-wide elastic strip encased in the hem. Soles shall be secured with a 12.5-mm (1/2-in.)-wide elastic strip sewn inside the cover across the instep. Soles shall be continuous, nongrooved, and shall contour the foot, extending 50 mm (2 in.) upward at the heel for support. They shall be fabricated of a nonskid material having a kinetic coefficient of friction of 1.45 outside and 1.25 inside, or greater, per ASTM D 1894. Sole materials must meet the same KSC static dissipation requirements as the coverall fabric. A label denoting size and fabric type shall be sewed to the inside arch of each cover. Shoe covers are not recommended for use in environmentally controlled areas for processing spacecraft because pant legs are not enclosed.

[7]Conductive Chemstat 939 (Stern & Stern) has been found to be satisfactory.

7. Garment Cleaning

7.1 Facilities for washing cleanroom garments shall meet the criteria given in Air Force T.O. 00-25-203, paragraph 8.3.d.

7.1.1 Initial Cleaning: all garments shall be water-washed a minumum of two times prior to initial use in a cleanroom.

7.1.2 Water Wash: soiled garments shall be washed in detergent and hot water to remove water soluble contaminants, including salts from perspiration. Wash water shall be neutralized to a pH of 7.0 since polyester fibers degrade in a highly alkaline environment. Water temperature must be no higher than 55°C (130°F) to avoid wrinkles in the garment. Washing shall be followed by tumble drying in a steam heated dryer with HEPA filtered air flow. An automatic particle counter shall be located on the hot air exhaust line to monitor particles. Reuse of wash water is not permissible.

7.1.3 Drycleaning: garments shall be drycleaned after aqueous laundering to remove organic contaminants such as oils, greases, and fatty acids. Soiled garments shall be loaded into a large capacity drum-type machine from a room which need not have a controlled environment.

7.1.4 Cleaned and dried garments shall be unloaded via an interlocking access door directly into a cleanroom equipped with unidirectional air flow and a maximum environment of Class 100 per FED-STD-209D. The organic solvent, perchloroethylene, shall be used to dryclean along with a small amount of sodium-free detergent as a softening agent. Soap concentration and nonvolatile residue in the cleaning solution shall be monitored continuously. A distillation system shall be activated automatically when nonvolatile residue test results indicate that the perchloroethylene contains unacceptable levels of dissolved contaminants such as oils, greases, fatty acids, and chemicals. The solvent may be continuously reused if it passes through a series of filters which reduce the contaminants down to a submicron level and if the solution is sufficiently distilled to remove the dissolved organic residues. There shall be an annual certification of the facility by an outside source.

7.1.5 Packaging: cleaned garments shall be packaged in an environmentally controlled area having unidirectional air flow and a maximum environment of class 100, per FED-STD-209D. Employees shall remove street clothes and don cleanroom coveralls, head, face, hand, and foot covers. Garments shall be changed daily. Packaging materials and related supplies shall be introduced into the clean room via an interlocking pass-through window. All items shall be cleaned prior to entry into the cleanroom. Cleaned garments shall be packaged in polyethylene bags and heat sealed. Sizes shall be clearly visible from outside the sealed bags.

7.2 Sampling: cleaned and packaged garments shall be inspected periodically to ensure product acceptability. Particulate contaminants shall be evaluated according to the methods described in ASTM F 51-68(1984) and MIL-STD-105D. If the particle count of a garment exceeds 2000 particles 5.0 μm and larger per 0.1 m^2 (1 sq ft), the garment should be inspected using a microscope. If the garment is shedding fabric, it should be discarded. If it has been improperly processed, other garments from the same processing are likely to be unacceptable and the entire lot should be rejected and reprocessed. Analytical procedures for determining extractable residues from cloths are described in SD-TR-89-63. The test method described in ASTM E 1235-88 may also be used if the 0.1-m^2 (1-ft^2) stainless steel sample is replaced by a piece of fabric of equivalent size.

8. Operational Processing

8.1 Useful Life: polyester garments shall withstand 15,000 wash cycles, and Nomex nylon shall withstand 12,000 wash cycles. This processing shall cover approximately 2 years of continuous usage per ASTM D-4157-82. Garments shall be inspected after 2 years of continuous use and replaced if excessive signs of wear are observed.

8.2 Frequency of Change: a minimum of three garments shall be supplied per wearer. Recommended garment changes for the various classes of clean rooms, based on one person per 100 square feet of floor area, are given in IES-RP-CC-003-87-T, and in U.S. Air Froce T.O. 00-25-203, paragraph 7.1.6. The user shall establish procedures for controlling and inspecting garments so as to meet the requirements for product cleanliness.

8.3 Garment Repairs: the cleanroom officer shall segregate all damaged garments which can be repaired before sending them to the cleaning facility. Damage shall include tears, loose filaments, and seams that have opened. If damage is extensive, disposal of garments may be necessary. Repairs shall be made outside the cleanroom, and shall be performed in a manner that shall eliminate frayed edges and puckered areas. Repairs shall be completed prior to final processing by water-washing and drycleaning.

8.4 Certification: a yearly certification shall be performed on the fabric used to construct garments to ensure that no variation occurs from lot to lot.

Table A1. Body Measurements for Specified Sizes of Cleanroom Bunnysuit Coveralls, Average Length (USA)

(in inches)

	(30–32) XS	(34–36) S	(38–40) M	(42–44) L	(46–48) XL	(50–52) XXL	(54–56) XXXL	(58–60) XXXXL	(62–64) XXXXXL
Chest	40	42	46	50	54	58	62	66	70
Waist	38	40	44	48	52	56	60	64	68
Hip	41	44	48	52	56	60	64	68	72
Trunk	65	68	68	73	75	77	79	81	83
Back Yoke	17¼	18½	20	22	24	26	28	30	32
Leg Inseam	29½	30	30	32½	32½	32½	32½	32½	32½
Sleeve Inseam	19	19	21	21	21	21	21	21	21
Wrist				11½	11½	11½	11½	11½	11½
Length				63	64	65	66	67	68

POINTS OF MEASURE:

Chest:	With coverall buttoned, distance around chest, 1 in. (2.5 cm) below bottom armhole seam.
Waist:	With coverall buttoned, distance around center of waistband.
Hip:	Distance around hips, measured at bottom of front fly.
Trunk:	With front of waistband even with back waistband, double distance between back collar seam and bottom of crotch.
Back Yoke:	Measure across shoulder between points where shoulder seams join the arm seams.
Leg Inseam:	Crotch seam to bottom of ankle.
Sleeve Inseam	From under ampit to wrist.
Length:	Measured from top of garment at collar to bottom of ankle.

Table A2. Body Measurements for Specified Sizes of Cleanroom Bunnysuit Coveralls, Longs (USA)

(in inches)

	(30–32) XS	(34–36) S	(38–40) M	(42–44) L	(46–48) XL	(50–52) XXL	(54–56) XXXL	(58–60) XXXXL	(62–64) XXXXXL	Tolerance
Chest	40	42	46	50	54	58	62	66	70	± 1 in.
Waist	38	40	44	48	52	56	60	64	68	± 1 in.
Hip	41	44	48	52	56	60	64	68	72	± 1 in.
Trunk	68	71	73	76	78	80	82	84	86	± 1 in.
Back Yoke	17¼	18½	20	22	24	26	28	30	32	± 1 in.
Leg Inseam	31	32	32	34	34	34	34	34	34	± 1 in.
Sleeve Inseam	21	21	23	23	23	23	23	23	23	± 1 in.
Wrist				11½	11½	11½	11½	11½	11½	± ½ in.

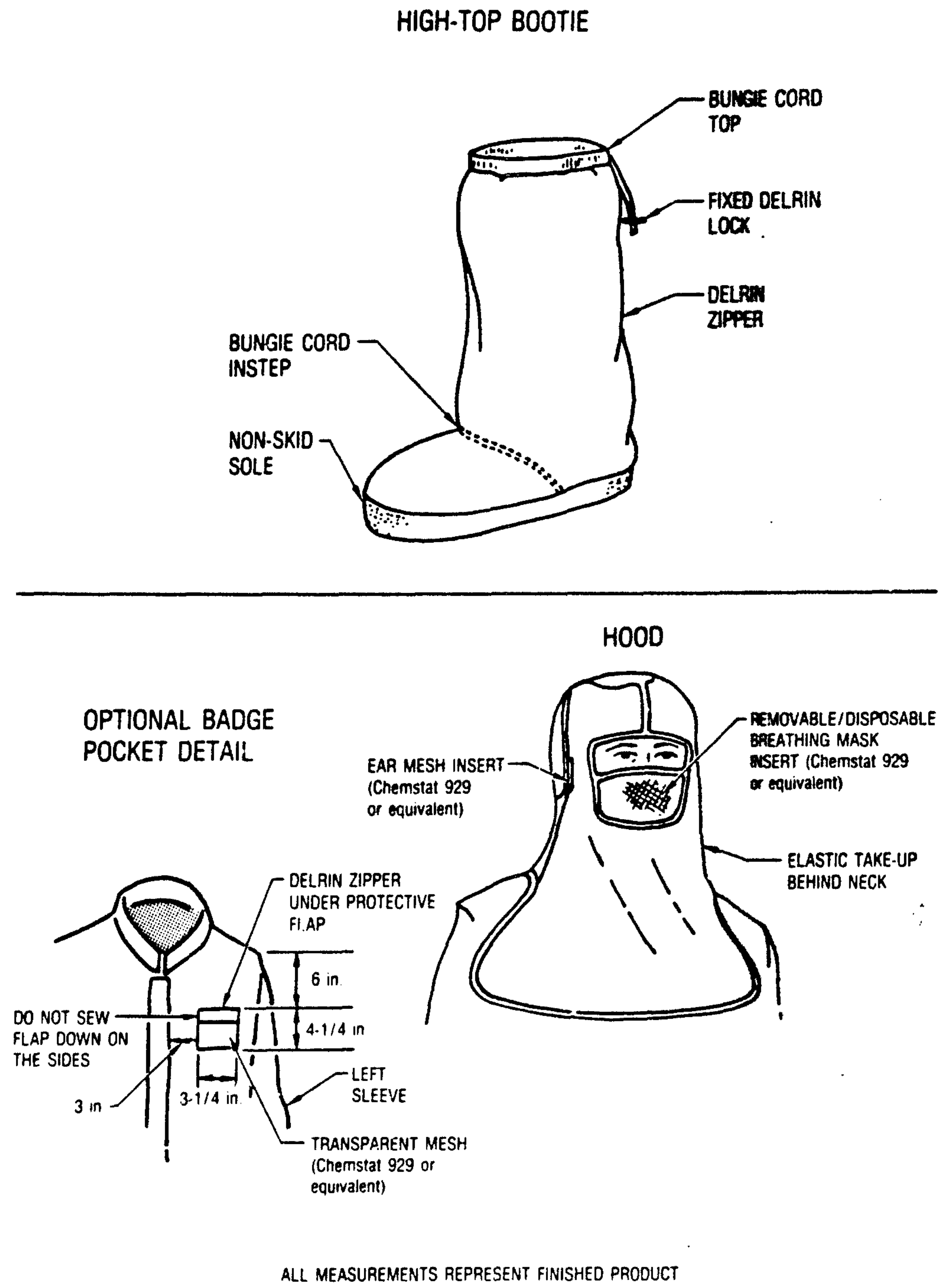

Fig. A.1 Footwear and Headwear for Hazardous Use

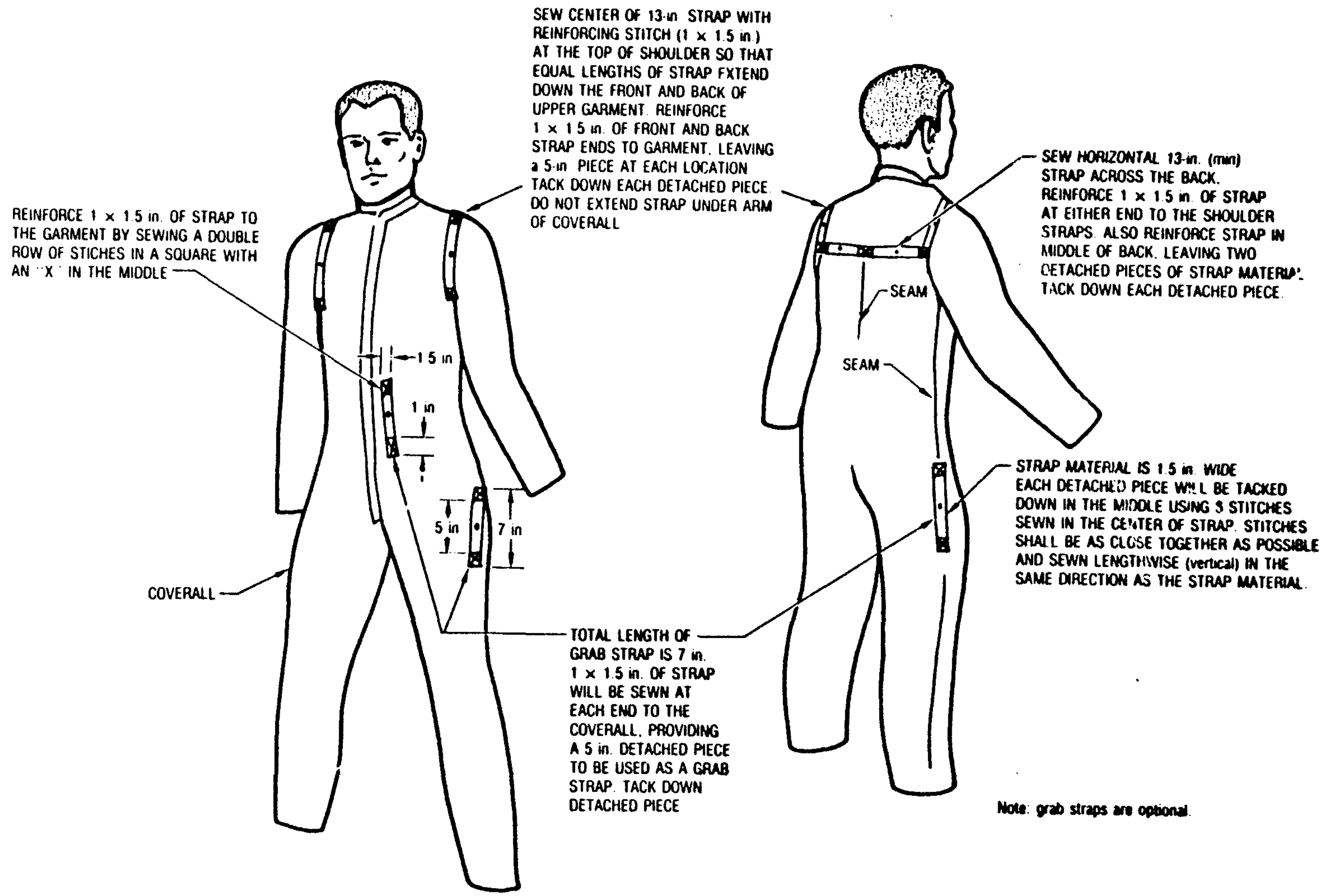

Fig. A.2 Nomex Grab Strap Details

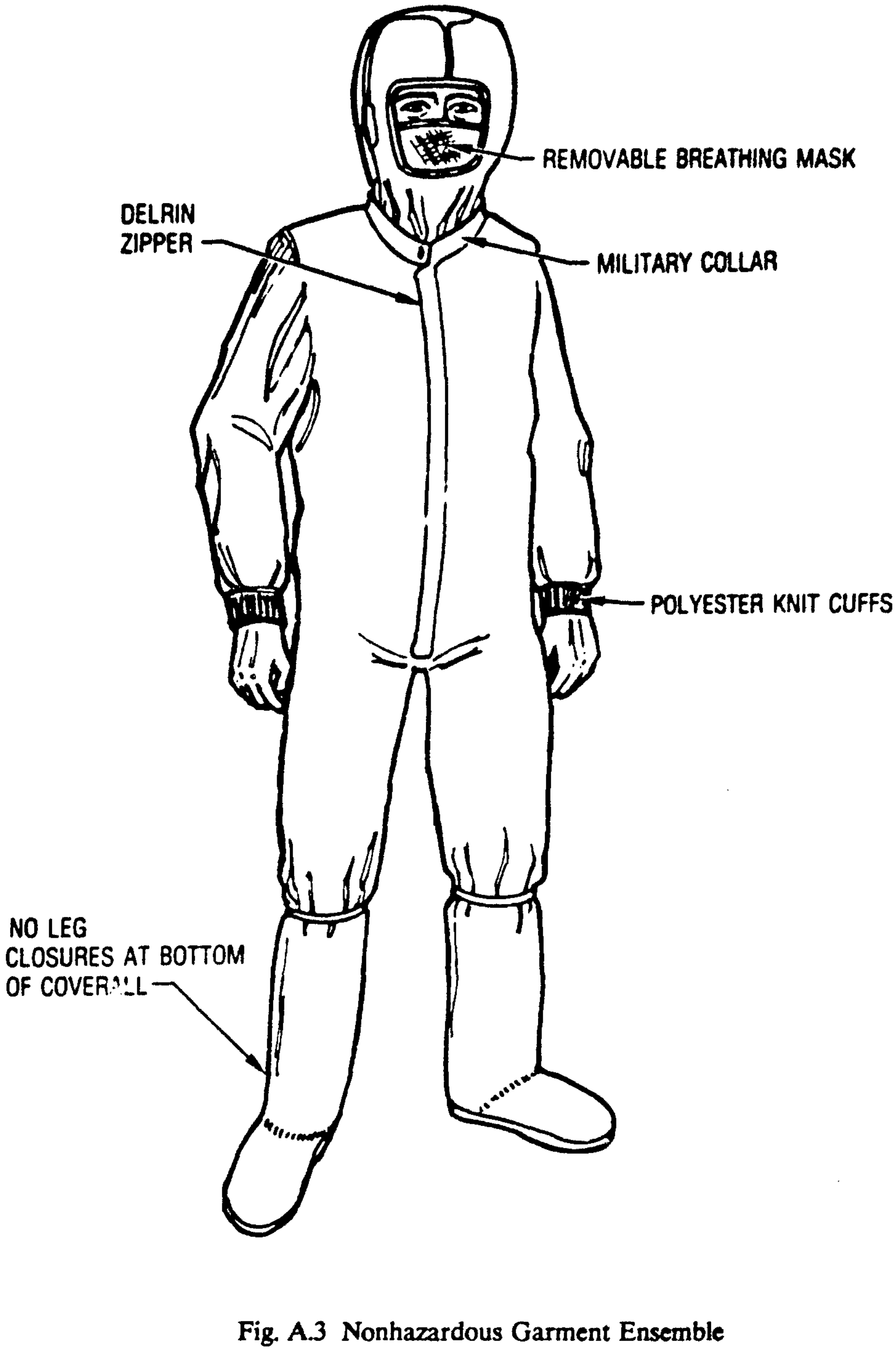

Fig. A.3 Nonhazardous Garment Ensemble

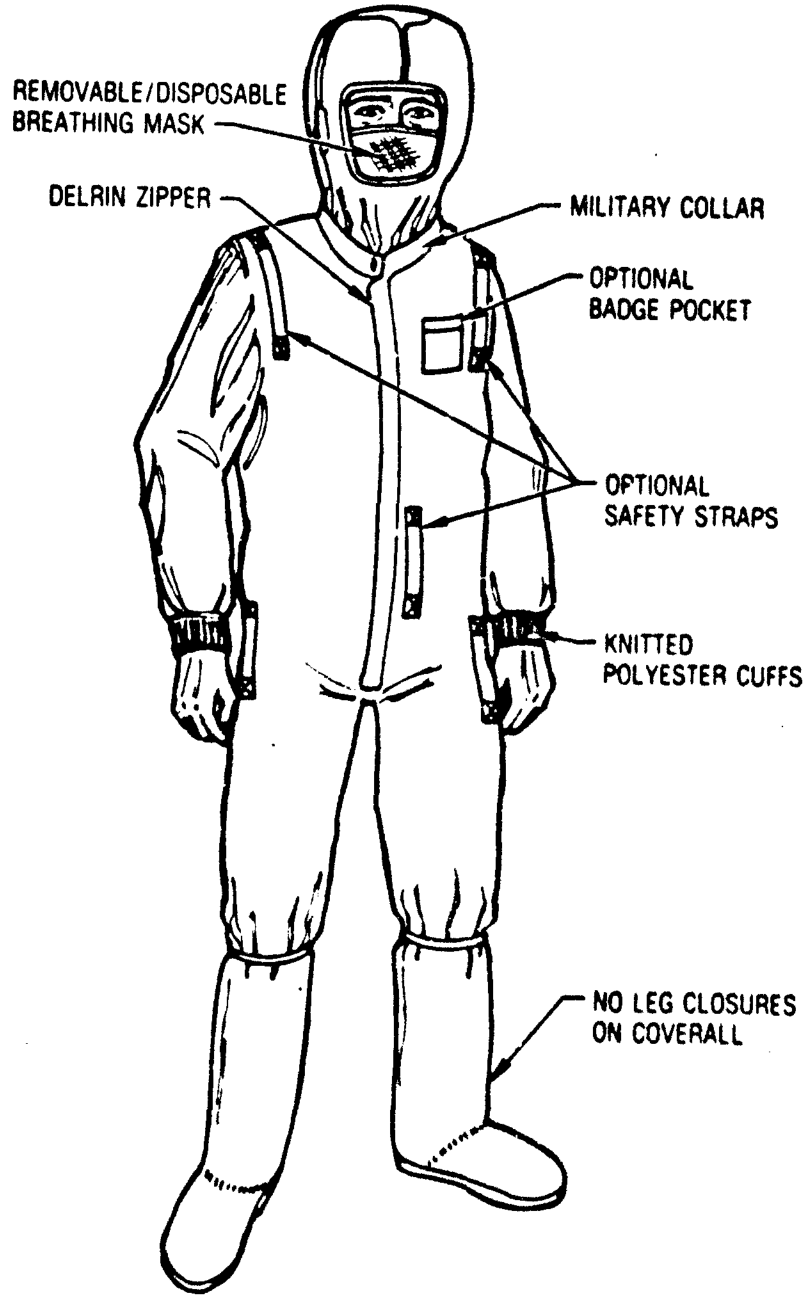

Fig. A.4 Hazardous Garment Ensemble

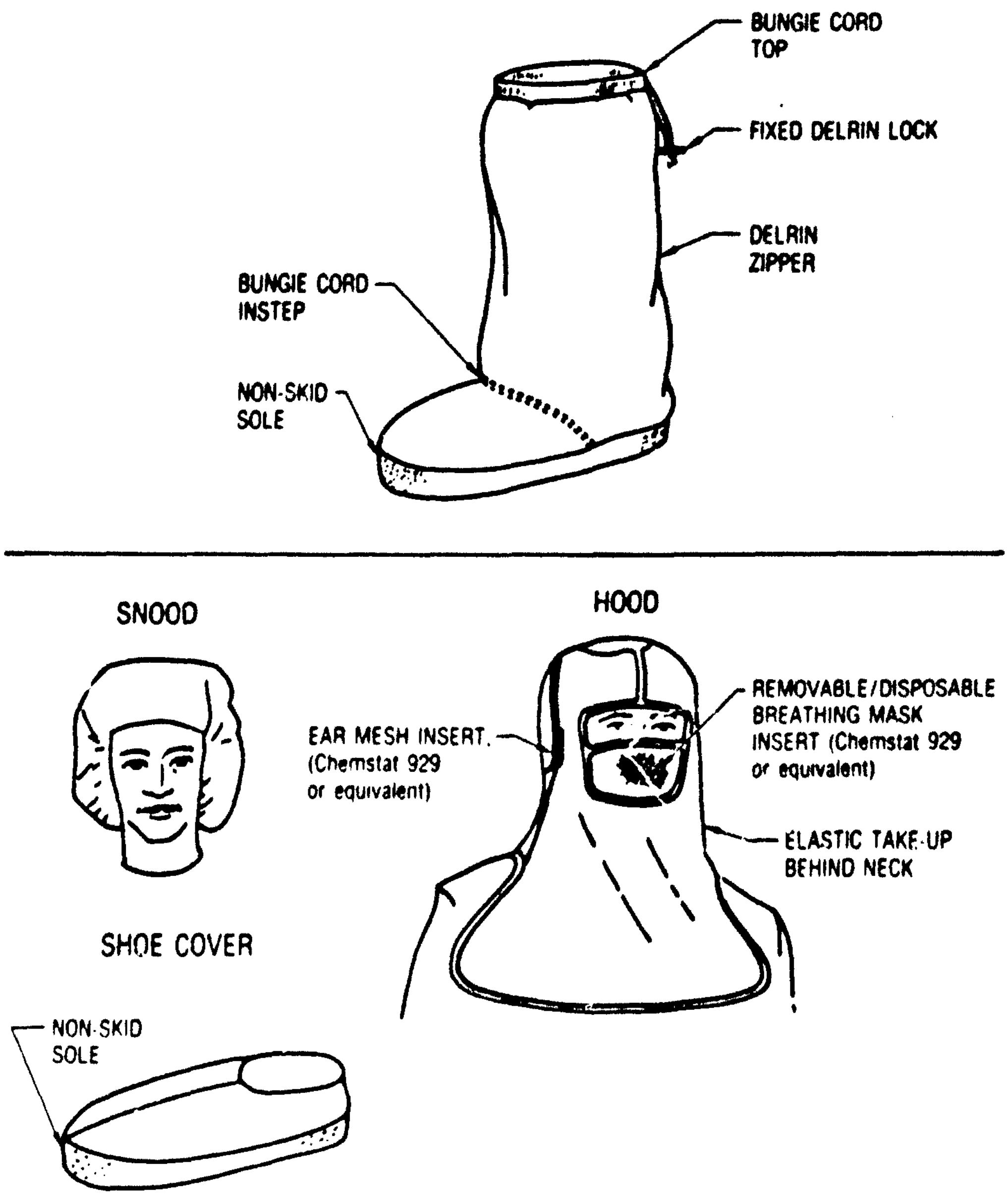

Fig. A.5 Footwear and Headwear for Nonhazardous Use

APPENDIX B

LIST OF FABRICS

ASO-100 is proprietary with Angelica Uniform Group. This fabric is covered by U.S. Patent number 4,422,483. The base fabric is continuous-multifilament nontexturized polyester in a herringbone weave. The conductor is continuous-filament carbonized nylon.

C3 is made by Klopman Uniform Fabrics, a division of Burlington Industries, Inc. The base fabric is a superdense weave of 100% multifilament Dacron polyester incorporating a polyester-coated continuous-filament carbonized nylon. Unique moisture-release properties offer workers extra comfort during long hours on the job.

Cubic-10 is proprietary with Angelica Uniform Group. The base fabric is continuous multifilament nontexturized polyester in a twill weave. The conductor is continuous-filament polyester with carbon. The fine denier yarns used in the fabric provide a soft hand and give noticeable improvement in employee comfort levels.

ChemStat 909 is made by Stern & Stern Industries, Inc. The base fabric is continuous-multifilament nontexturized polyester in a twill weave. The conductor is continuous-filament carbonized polyester in a raised 6.5-mm (1/4-in.) grid pattern. The fabric has a permeability of 6.6 cm3/sec (14 cfm) and is woven of very small filament yarns. The fabric comes in nine colors and in white.

Chemstat 919 is a Stern & Stern product. The base fabric is continuous-filament Nomex aramid in a twill weave. The conductor is continuous-filament carbonized polyester in a raised 6.5-mm (1/4-in.) grid pattern. The fabric is flame retardant and meltproof.

Chemstat 929 is a Stern & Stern product. The fabric is 100% polyester filament used primarily for face masks. The hole size is rated at 35 μm (smallest facial hairs are 50–85 μm).

eV-Gard, a product sold by the Vidaro Corporation, is basically a Dacron polyester in a herringbone weave, with Monsanto conductive nylon fibers incorporated for the prevention of electrostatic discharge.

Selguard II is a product of Teijin in Japan. The base fabric is continuous-multifilament polyester in a twill weave. Metalin organic and electrically conductive fibers are woven in at 2 cm (0.8-in.) intervals. The fabric utilizes texturized filament yarns in the fill direction (horizontal). This provides a soft hand and a more comfortable fabric.

Note: Every effort was made to include all acceptable fabrics. Some acceptable fabrics, however, may have been inadvertently excluded. This is unintentional.

APPENDIX C

LIST OF FABRIC AND GARMENT SUPPLIERS

1. Angelica Uniform Group, Plantswear Division, P.O.Box 466, St. Louis, Missouri 63166-0466, (314) 889-1111.
2. Colonial Glove and Garment Inc., 1800 Ocean Avenue, Ronkonkoma, New York 11779-6528, (516) 588-6900.
3. DuraWear Apparel, 9116 Virginia Road, Lake in the Hills, Illinois 60102, (815) 455-3777.
4. Klopman Uniform Fabrics, Division of Burlington Industries, Inc., 1345 Ave. of the Americas, New York City, New York 10105, (212) 621-3358.
5. Stern & Stern Industries, Inc., 188 Thatcher Street., Hornell, New York 14843, (607) 324-4485.
6. Vidaro Corporation, 333 Martinel Drive, Kent, Ohio 44240, (216) 673-7413.
7. Worklon Division of Superior Surgical Manufacturing Co., Inc., Seminole Blvd. at 100th Terrace, Seminole, Florida 33542, (813) 397-9611.

Note: Every attempt was made to compile a complete list; suppliers may have been inadvertently excluded. This is unintentional.

APPENDIX D

LIST OF GARMENT RENTAL AND PROCESSING COMPANIES

1. Araclean Services, Inc., Marketing Headquarters, P.O. Box 458, LaGrange, Illinois 60525, (312) 352-3200.
2. Cleantech, 3415 Northland Drive, Austin, Texas 78731, (512) 467-6810.
3. Micron-Clean Uniform, Inc., 57 Plattekill Turnpike, Newburgh, New York 12550.
4. Prudential Overall Supply, General Offices, 1661 Alton Ave., P.O. Box 11210, Santa Ana, California 92711, (714) 250-4855.

Note: This is intended to be representative and is not intended to exclude any companies intentionally.

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security projects, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development, including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and environmental chemistry.

Electronics Research Laboratory: Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, rf systems, electromagnetic propagation phenomena, space communication systems.

Materials Sciences Laboratory: Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.